inter.noise 2012
august 19-22
new york city, usa
Quieting the World's Cities

Urban form as environmental noise indicators

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The urban form affects all systems and all species in an urban context and influences their behavior from the emission of noise, through its course until reaching the receiver, affecting the global climate. This paper seeks to address the problems of the urban environment as an area of interaction between urban forms and urban noise. This interaction is intended to be monitored by urban indicators, comparing the effects of noise propagation in an urban form model. The model of noise prediction (NMPB96), allows the development of studies about noise in facades (Ld, level of noise during the day), resulting in colors associated to noise categories. This study will allow the creation of different scenarios and to foresee, still in the draft phase, the facades exposed to a higher noise level. The effects of noise in facades can be, then, minimized in advance, by adjusting the layout of their typology. In order to validate the model and its results, we compared the values obtained at selected locations by modeling them. The validation of the theoretical curves was done in two phases. The first validation involved the measurement and the modeling of the selected real forms by comparing their receptor points. The second validation was done by calculating the average noise level on the facade of the modeled real forms, and then validated by comparing the calculation results of the indicators of form and behavior of the theoretical forms in order to correspond to its homonymous removed and measured in its real context. The study allowed the creation of different scenarios and anticipates, from its conception stage, the facades which have higher exposure to noise. Therefore, it is possible to minimize, in advance, the effects of noise on the facades, using the adjustment of the layout and configuration of the building form. The results showed that the physical characteristics of urban form influence sound propagation in a certain area. The urban parameters are important for determining sound of urban environment and, therefore, cannot be disregarded.

1 INTRODUCTION

The importance of urban form on sustainable development has been recognized in recent years. Since the late 20th century, a number of countries have adopted urban form policies in environmental planning (National Physical Planning Agency) [1]. Urban form directly affects habitat, ecosystems, endangered species and water quality through consumption, fragmentation and replacement of natural cover with impervious surfaces. Urban form also affects indirectly travel behavior, which, in turn, affects air quality, global climate and noise [2].

The United States Environmental Protection Agency [3] stated, in 1972, noise as a pollutant and identified it as one of the most common problems that affects the quality of life in urban areas.

Nowadays, the United States Environmental Protection Agency [3] considers noise as an environmental problem affecting the largest number of people on the planet, after air and water pollution. The problem has proved difficult to control due to the existence of a wide variety of sources, methods of noise exposure assessment or indicators that can undoubtedly describe the noise [3].

However, several studies have focused on the modeling of air pollution and noise in different urban forms [4, 5, 6,7, 8and 9].

Borrego[8] considers the evaluation of environmental noise through useful noise mapping and prediction, which allow us to view and quantify the environmental noise, contributing to an appropriate planning of the urban sound environment. The main objective of Borrego's [11] study was to determine how the interaction between sound sources and urban form influence a certain noise environment.

Guedes[9], on the other hand, proposes a prototype system for modeling the noise and air pollution. The system integrates a traffic noise model, an operational model of air pollution, a digital map, a model of urban landscape and a geographic information system (GIS). Guedes[12] concluded that urban form, with narrow roads, with road networks and complex denser intersections lead to a decrease in volume of traffic, which, in turn, reduces noise pollution.

The studies carried out from Borrego[8] to Guedes [9] show the need for further studies on noise pollution and on its consequences on environment and human beings. In past decades, many authors agreed that noise and its variability must be taken into account in environmental research. [2, 10, 11, 12, 13 and 14]

Accordingly, the innovative and pioneer character of the study is evidenced by the integration of emerging techniques, including software simulation and noise modeling, and it represents an effort to model the territorial reality in a computing environment, further exploring the complexity of urban form, in order to minimize their effects on noise propagation.

2 URBAN NOISE

The concept of noise is defined as the variation of atmospheric pressure, within the limits of the band's range and frequency to which the human ear responds. Since the human ear is more sensitive to certain frequencies than others, the level of disturbance varies according to the spectral content of noise.

Therefore, the definition of environmental noise is expressed by a logarithm of the ratio between the measured sound pressure and the reference pressure. Sound pressure level is called Lp and it is expressed in Bel (B) or, multiplying by 10, in decibels (dB), as we can see in Eqn (1):

$$Lp=10\times\log10\ (p/p0)^2=20\times\log10\ p/p0 \qquad (1)$$

Where *Lp* is the sound pressure level expressed in dB; *p* is the real value of sound pressure expressed in Pascal and *p0* is the reference sound pressure and corresponds to the minimum threshold of human hearing (p0 = 2 x 10-5 Pa)

In order to characterize the sound pressure level emitted but not received by the human ear, the sound pressure level expressed in dB is weighted by a coefficient that depends on frequency. Sound pressure level is, then, measured by considering the weighting curves A, B and C.

Therefore, for the measurement of environmental noise and annoyance, weighting curve A is more frequently used, because it is the one that best correlates the measured values with the sound awkwardness. Thus, in studies of noise environment, the sound pressure level is usually expressed in dB (A).

The noise indicators are determined for parts of day: daytime, evening and night periods within a period of one year. ISO 1996-2:1987 [15] defines the average noise level in the long term as a sound pressure level equivalent continuous A, which can be determined by calculation. It takes into account variations in the noise source and in the weather conditions that influence the noise propagation. For the day period we used the equivalent continuous sound level indicator (Leq), which is an average indicator, according to the RGR (General Noise Regulations, approved by Decree Law No. 9 / 2007 of January 17) [16].Daytime is the period between 7 a.m. and 8 p.m.

2.1 What Influences the Propagation of Noise and how it can be measured

Noise is emitted by a sound source or a set of sources and spreads from the source in mechanical concentric waves and in slightly spherical forms.

The noise decreases when the distance between the source and the receiver station increases. This reduction depends on several factors such as the font type, the absorption characteristics of the surrounding soil and the existence of barriers. In addition to the already mentioned factors, the weather conditions also have a strong influence on the propagation of noise, and wind and temperature are the factors with more emphasis.

When calculating the propagation of acoustic power that reaches a particular receptor, several mitigating factors should be taken into account, according to Newton [5]: the attenuation due to geometric divergence, the attenuation due to absorption by air, the attenuation due to diffraction, the effects due to the soil surface and vertical absorption.

There are numerous models available in the market of noise forecast, which is an important working tool in modeling the acoustic situation, as reported by Bertellino [17]. The method, known as the New Method of Traffic Noise Forecast (NMPB 96) was developed in France in 1996. This is an interim method recommended by Directive 2002/49/EC [18] of the European Parliament and the Council of 25th June on the assessment and management of environmental noise. The noise prediction method should provide secure results, which represent the real situation of noise levels under any emission and propagation conditions (OECD, 1995) [19].

Achieving these secure results, depends on the assessment of noise emissions due to traffic flow and assessment of noise attenuation between the source and the receiver.

3 URBAN FORM TYPOLOGIES

The urban form is defined on the relationship between outer space and buildings volume that exist in a specific soil or landscape. The presented forms are selected from the "Neighborhood Proximity Model" and given a numerical nominal designation in order to be easy to read and it is divided in tree groups illustrated in the following figures (Fig.1 and Fig.2). The theoretical model of Pedro[20], the "Neighborhood Proximity Model", which designs parameters that have been considered and applied to each of the spaces that compose the neighborhood proximity, was applied to the following ten forms:

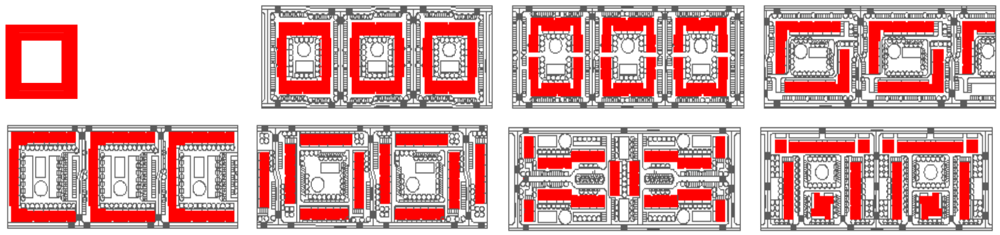


Fig.1 Illustrations of closed implantation (Form Type 1, 2, 3, 4, 5, 6, 7)

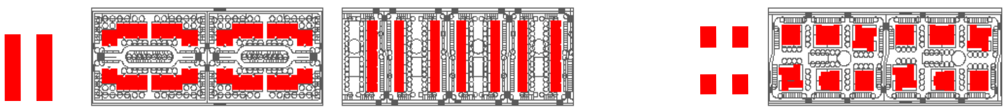


Fig.2 Illustrations of linear (Form Type 8, 9) and punctual implantation (Form Type 10)

The urban forms are divided in three groups, depending on the type of implantation. The first group is representative of the Closed implantation, where the buildings are clearly delimited by the space outside buildings and this space surpasses the distance equal to or less than a quarter of the total length of the perimeter of the outer space. The second group presents the most common types of implantation: the Linear implantation, where the buildings only suggest the shape of the outer space which interrupt buildings, in a distance greater than the fourth part and less than half the total length of the perimeter of the outer space. The last and unique, but representative example, is the Punctual implantation, where the buildings are not delimited by the outer space, instead they surpass a distance greater than half the total length of the perimeter of the outer space.

The ten neighborhood typologies were defined according to two perspectives. The programmatic perspective, which is defined as sets of neighborhoods proximities, with identical functional programs (such as the number of houses, the number of inhabitants or similar occupation index).The morphological perspective is a set of neighborhoods proximities, with similar formal characteristics (such as the form of implementation of the set of buildings, the form of buildings in relation to streets, the form of road local access, the number of floors above the main entrance of the buildings of neighborhood proximity or the number of habitation from neighborhood proximity).

3.1 Quantitative Indicators of Urban Form

Trying to characterize the urban form is, in spite of the growing interest, an exploration of real differences which are illustrated in incipient studies. Only recently more systematic classifications have emerged as a mean of quantitative methods and analysis of issues in these debates.

Torrens[21] captured eight dimensions of expansion: density, continuity, concentration, clustering, centrality, nuclearity, mixed uses, and proximity. Wassmo [22] has created an expansion index based on four factors (i.e., residential density, mixed neighborhood, business strength and accessibility) for U.S. cities. Galster [23] used four quantitative variables (i.e. metropolitan size activity, intensity, degree distribution and degree of clustering) to differentiate "compactness" of expansion. Others such as Ewing [24], Tsai [25], Longley [26], employed multidimensional indicators to measure the "compactness" in specific neighborhoods or cities.

The indicators that we intend to study have a dimensional nature, which can be applied to other typologies with external specificities from the presented models.

3.1.1 Occupation Index or Rate of Soil Occupation (% P) - is the indicator that relates the quotient between the surface of implantation and the land area.
The calculation of the Occupation Index (% P) is presented by Eqn (2):

$$\%P = \frac{\sum_i Si}{A\ t} \tag{2}$$

Where Si is the Patch Area [m^2] and $A\ t$ the Total Area [m2]
The urban form that has the largest area of implantation will have the higher content (% P).

3.1.2 Compactness Index (CI) -This indicator measures not only the shape of the urban area (urban patch), but also considers the global urban landscape fragmentation according to Li [27].
The Compactness index (CI) is calculated based on de Eqn (3):

$$CI = \frac{\sum i\ \frac{Pi}{pi}}{N} = \frac{\sum i\ \ 2\pi\sqrt{\frac{si}{\pi}}/pi}{N} \tag{3}$$

Where si is the Patch area [m^2], pi is the Patch perimeter [m]; Pi is the Circle perimeter an area of si [m] and N is the Total number of Patches [-]. An urban area according to Huang [28] has higher values of CI when more regular and more compact the urban forms are.

3.1.3 Porosity Index (ROS) - is the permeability indicator which measures the proportion of open space, compared to the total urban area.
The Index of Porosity or Permeability is calculated by Eqn (4) shown below:

$$ROS = \frac{s\acute{}}{\sum_i Si}\ x\ 100\ \% \tag{4}$$

Where $s\acute{}$ is the Summation of area of all the "holes" within the urban area studied [m^2] and Si is the Summation of area all patchs [m^2]. An urban area has higher levels of ROS when urban forms have higher open spaces. This indicator is also called as the ratio of open spaces.

3.1.4 Complexity of the Perimeter Index (Fractal) - The complexity is defined by the perimeter fractal dimension. This index describes according to Bennion [29] and Sanches [30] the complexity of the perimeter of an urban area through the relationship between perimeter and area.

For the research we used the average fractal dimension of urban patches weighted by the area. The value of fractal dimension is between 1 and 2. Lower values are obtained when the patch has a simpler form (the fractal dimension of a circle is equal to 1).If the perimeter is more complex and irregular; fractal dimension is greater. The Fractal index (Fractal) is calculated based on the Eqn (5):

$$fractal = \sum_{j=1}^{n} \left(\left(\frac{2\ln\left(\frac{pi}{2\sqrt{\pi}}\right)}{\ln(si)} \right) \left(\frac{Si}{\sum_{j=1}^{n}\ Si} \right) \right) \tag{5}$$

Where *pi* is the Patch perimeter [m]; *Si* is the Patch area [m^2]; and *n* is the Total number of Patches [-].

The combination of typologies and indicators presented previously served as the basis for the development of many different scenarios, as a base comparable to the analysis that we intend to study. Thus, the ten urban forms submitted are based on a grid of 210 m x 140 m grid, with a total gross floor area of 29,400 m^2 and with the following results presented in Table1.

Table 1 Results of calculations of the form indicators

Form Indicator	Form1	Form2	Form3	Form4	Form5	Form6	Form7	Form8	Form9	Form10
P[%]	25.63	24.64	19.62	23.69	22.00	17.47	19.45	21.99	19.72	19.44
CI[-]	0.38	0.49	0.48	0.35	0.62	0.68	0.72	0.61	0.57	0.82
ROS[%]	74.37	74.36	80.38	76.31	78.00	82.53	80.55	78.01	80.28	80.56
Fractal[-]	1.25	1.20	1.21	1.28	1.15	1.16	1.14	1.15	1.17	1.07

4 THE INFLUENCE OF URBAN FORM ON THE PROPAGATION OF NOISE

Each of the scenarios developed is served by two local distributor roads and local access roads. For this calculation, only the local distributor roads were included in the assessment. The routes considered in each developed scenario possess the following characteristics:

- asphalt pavement without inclination;
- fluid flow of road traffic (300 total vehicles/h with 5% heavy);
- velocity of 50 km/h.

The evaluation of noise levels at the facades, we developed a square grid calculation over all the facades of 1.5 m x 1.5 m and a distance from the facade of 0.5 m. The number of floors exposed to noise ratio was 4 floors, each 3 m high (ground floor included) making a total of 12m of height.

The noise level at the buildings facades, in the selected urban form, was calculated for each of the nodes of the calculation grid created for this purpose. The arithmetic average noise level, and the maximum and minimum noise levels were calculated of the 10 urban forms and the resulting values are summarized in Table 2 below.

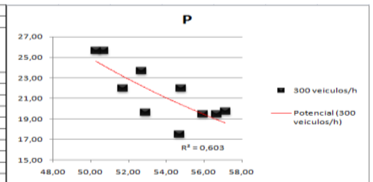
Table 2 Summary of Results of Noise Levels

Urban Forms	Leq	Lmax	Lmin	Number of calculations nodes
Form 1	50.67	64.33	35.90	6216
Form 2	50.27	64.80	35.58	6909
Form 3	52.90	64.22	38.02	5439
Form 4	52.70	68.83	35.93	6489
Form 5	54.79	63.77	44.17	6272
Form 6	54.72	63.08	41.08	5474
Form 7	55.94	64.85	44.35	5866
Form 8	51.70	63.15	35.80	6273
Form 9	57.14	64.07	48.90	5411
Form 10	56.68	64.04	44.99	5250

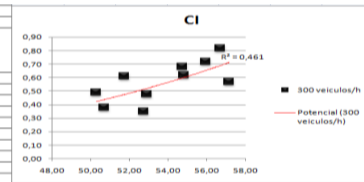
The approach showed that in the same area that we call Reference Area, the 10 selected forms, with different areas of implantation, with different number of forms or patches and separate provision of the forms and how they relate to the driveway and among each other, obtaining tendency curves that relate form indicators and noise levels in a valid way.

Next, we present, all form indicators applied to the 10 urban forms and their respective exposure to noise levels. This way, we expect to obtain comparative results and some conclusions on how the urban form can influence the propagation of urban noise.

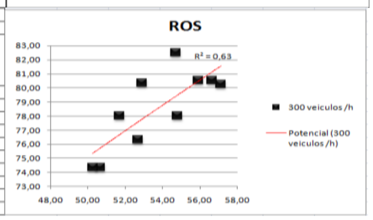
Noise	P	Form
dB(A)	[%]	
Arithmetic Average		
50,67	25,63	1
50,27	25,64	2
52,90	19,62	3
52,70	23,69	4
54,79	22,00	5
54,72	17,47	6
55,94	19,45	7
51,70	21,99	8
57,14	19,72	9
56,68	19,44	10



Noise	CI	Form
dB(A)	[-]	
Arithmetic Average		
50,67	0,38	1
50,27	0,49	2
52,90	0,48	3
52,70	0,35	4
54,79	0,62	5
54,72	0,68	6
55,94	0,72	7
51,70	0,61	8
57,14	0,57	9
56,68	0,82	10



Noise	ROS	Form
dB(A)	[%]	
Arithmetic Average		
50,67	74,37	1
50,27	74,36	2
52,90	80,38	3
52,70	76,31	4
54,79	78,00	5
54,72	82,53	6
55,94	80,55	7
51,70	78,01	8
57,14	80,28	9
56,68	80,56	10



Noise	Fractal	Form
dB(A)	m-1	
Arithmetic Average		
50,67	1,25	1
50,27	1,20	2
52,90	1,21	3
52,70	1,28	4
54,79	1,15	5
54,72	1,16	6
55,94	1,14	7
51,70	1,15	8
57,14	1,17	9
56,68	1,07	10

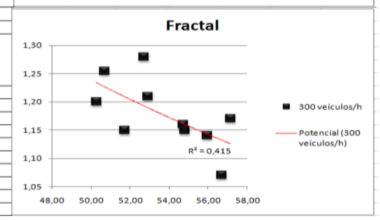


Fig.3 Relationship between Noise and Form Indicators of the 10 Forms

Through increasing Porosity or Permeability index (ROS), the average values of Leq also increase, this is explained by the fact that the greater the permeability of the urban form, the more easily sound waves are able to reach the buildings inside. With the increase of the Compactness index (CI), medium values of Leq also increase. This is due to the fact that the greater the regularity of urban forms, the lower the possibility of formation of shadow zones also known as protected areas.

Regarding to the Occupation Index (p), when it decreases, it generates facades with higher noise levels. The more "occupied" the soil, the more obstacles there are and, therefore, the greater the possibility to form protected areas.

Concerning the Fractal Index, the variation obtained is consistent with the variation of facades' noise levels. Fractal Index mainly describes the irregularity of the urban boundary. The higher this value is, the more irregular the shapes are. This fractal dimension varies from one to two: it approaches one, when forms have simple perimeters, and it approaches two, when forms are more complex. An indirect correlation between Fractal Index and the facades' noise levels is expected. The regularity of urban forms decreases the possibility of formation of shadow zones.

One of the objectives of this study is to establish the relationship between noise and urban form intents to promote the creation of protected areas or shadow areas in urban context.

5 VALIDATION

All forms selected are excerpts from residential and mixed areas taken from different parts of the city of Braga, and each one has different roadway and circulation characteristics, as well as distinct areas of occupation.

In order to give consistency to the theoretically developed curves, it is essential to validate the results. This procedure consists of comparing the values obtained from modeling with the measurement values taken at selected locations. The validation of the theoretical curves was made in two phases:

The first phase of validation was established, based on the values obtained by the receptor points, by comparing the measured "in situ" values with the respective modeled values. It can be clearly concluded that the three studied models of real forms validate the model.

The validation of the theoretical curves intends to make use of the modeled traffic volume in each road of the real forms and to distribute it by the actual number of roads, in order to obtain an average number of vehicles per hour.

In order to allow comparisons of the behavior of the three real forms in relation to the 10 modeled forms, it was necessary to proceed with the adjustment of the latter, with respect to the average traffic flow, traffic speed and type of pavement. Noise levels were calculated for the new traffic volumes for each one of the 10 modeled forms.

Finally, the ordered pairs (noise levels at the facade vs. form indicators) of the tree Real Forms were introduced in the tendency curves of the 10 modeled forms, in order to establish a comparison between the adjusted models and the real urban forms.

The behavior of the noise level of each of the real forms in relation to their theoretical models experienced no significant discrepancies or variations in the parameters of vehicle traffic, in which the adjustment of the number of vehicles per hour varied by changing the behavior of the noise in regard to the urban form. This is not only the volume or composition of road traffic that alone changes the behavior of noise, but also the volumetric composition forming a neighborhood unit.

In other words, the volumetry of the proposed neighborhood units, represented by the 10 types of urban forms, with its complexities and protrusions, can promote, or not, the existence of protected areas or shadow zones, which can, “per se”, decrease or increase, respectively, the exposure to noise in their respective facades. This means that the applied methodology allowed to obtain positive results.

6 DISCUSSION AND CONCLUSIONS

In the following figures, we present the vertical noise maps from de 10 modeled forms and the corresponding plants, so that the acoustically most critical areas can be seen, and to illustrate the most exposed and least protected areas that we call shadow areas. Each of the figures includes a label with a class of noise that illustrates the behavior of the propagation of noise, regarding the different presented forms types.

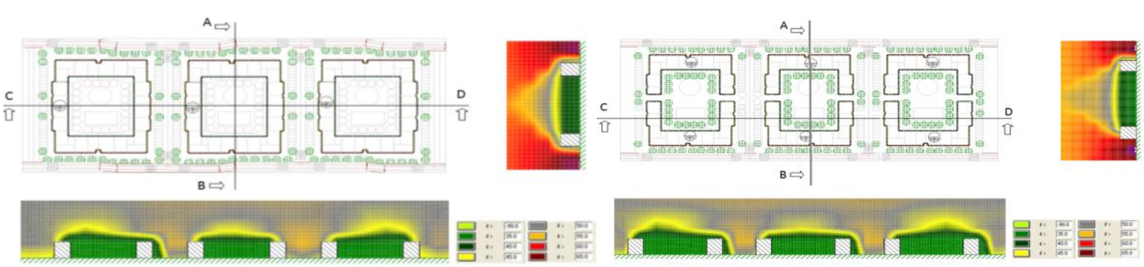


Fig.4 Plant and Vertical Noise Maps (AB e CD) from Modeled Form 1 and Form 2

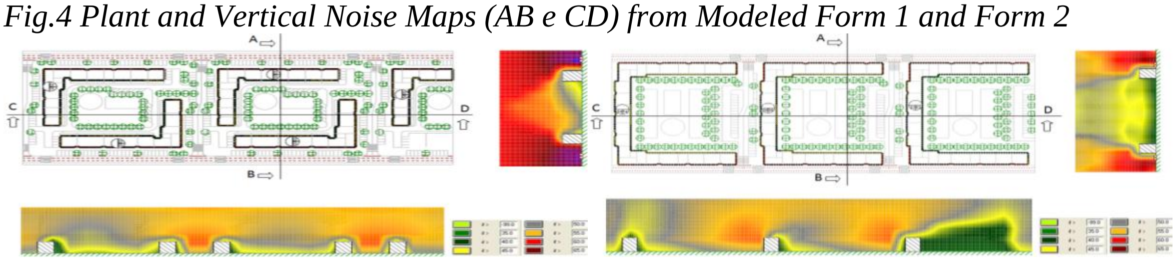


Fig.5 Plant and Vertical Noise Maps (AB e CD) from Modeled Form 3 and Form 4

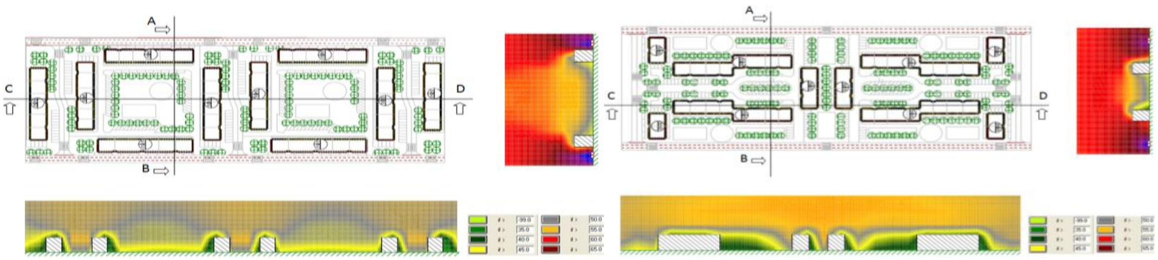


Fig.6 Plant and Vertical Noise Maps (AB e CD) from Modeled Form 5 and Form 6

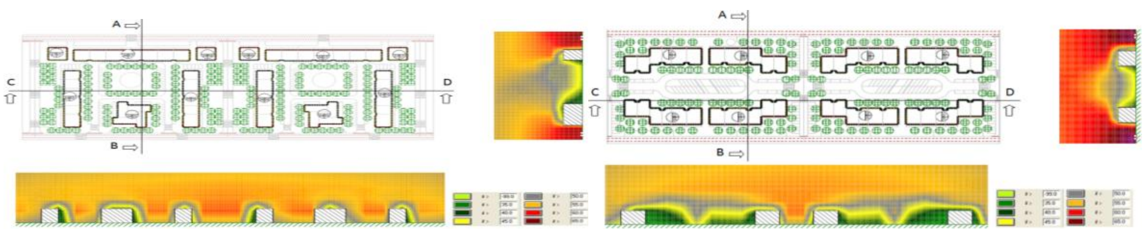


Fig.7 Plant and Vertical Noise Maps (AB e CD) from Modeled Form 7 and Form 8

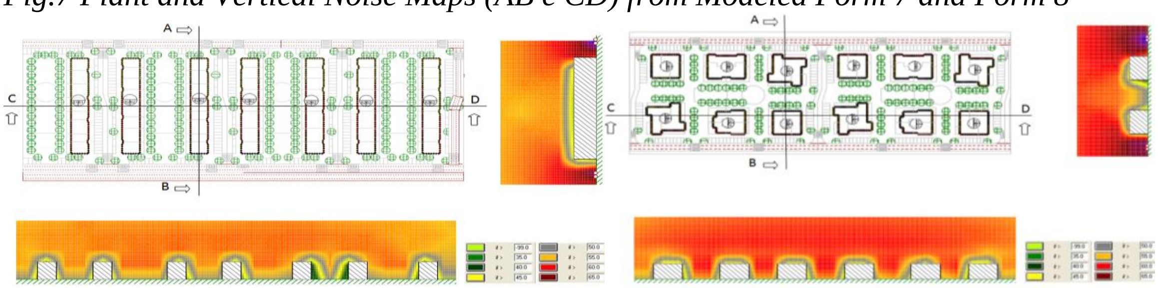


Fig.8 Plant and Vertical Noise Maps (AB e CD) from Modeled Form 9 and Form 10

In earlier forms it has always been possible to relate permeability / openings and the blocks' interior / exterior and the respective effects of noise on their facades. In the last two forms, this was not possible, because there was no disposition that allowed us to analyze the interior of a block, and that, itself, changed the evaluated noise levels. We can conclude that the studied Forms 1, 2, and 8, which include more protected areas, are the ones with lower noise levels. This effect is provided by the existence of the interior of the block and, as we have already seen, it concentrates the shadow areas, which in turn reduces its facades' exposure levels. Unlike this, Forms 7, 9 and 10 are the ones with the highest levels of noise and where the noise propagation finds no obstacles to its propagation, thus making it difficult to create protected areas or shadow zones.

The study allowed the creation of different scenarios and anticipates, at the conception stage, which facades have higher exposure to noise. Therefore, it is possible to minimize in advance the effects of noise in the facades, using the adjustment of the layout and configuration of the form of the building.

The results of Borrego[11] showed that the physical characteristics of urban form, such as construction, density, the existence of open spaces, the form and the layout of buildings, influence the sound propagation of a specific region.

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